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Title: Tracker Fits for shot 1s1674

Author(s): Menikoff, Ralph

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Tracker Fits for shot 1s1674

Ralph Menikoff

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1 Introduction

Gas gun shock-to-detonation experiments provide data for calibrating HE burn models. At LANL the principal diagnostic is a magnetic gauge package that provides data on the lead shock trajectory, which is used to determine the run-distance to detonation, and the lead shock speed with run distance, which together with jump-off velocity of the velocity gauges determines Hugoniot locus points for the reactants.

One method developed by Hill and Gustavsen [2002] for analyzing the shock trajectory is to use a fitting form based on the ODEs

$$\frac{\mathsf{d}}{\mathsf{d}t}\begin{pmatrix} x \\ U_s \end{pmatrix} = \begin{pmatrix} U_s \\ a_m \frac{D-U_s}{D-U_m} \exp\left(\frac{U_s-U_m}{D-U_m}\right) \end{pmatrix} , \tag{1}$$

where U_s is the shock speed, and the fitting form parameters are the final shock speed D, the shock speed at maximum acceleration U_m and the maximum acceleration a_m. There are also two parameters for the initial conditions of the ODEs; $x_0 = x(t_0)$ and $u_s = U_s(t_0)$. The fitting form works well when the trajectory data has a small scatter as seen in [Hill and Gustavsen, 2002, fig 4 and 5].

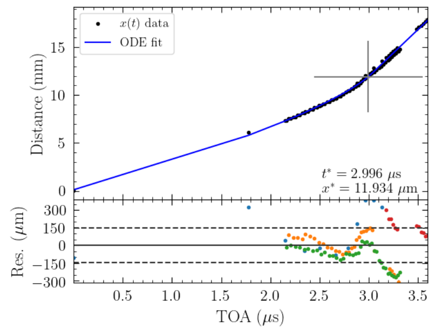
Issues with the ODE fitting form can arise when the scatter of the trajectory data is not small. To illustrate the effect on accuracy we examine the data fits for an experiment with PBX 9012, shot 1s1674. The gauge package is shown in [Burns and Chiquete, 2020, fig 1]. It contains 9 velocity gauges and 3 (left, right, center) tracker gauges. The spatial spacing of the tracker data points is roughly 4 time the spacing of the velocity gauges. There is also a stirrup gauge at the front surface of HE, which is used to set the time origin for the shock trajectory. The gauge package starts downstream of the HE surface. Noisy signals can lead to some missing data points from the tracker gauges.

In general, there is a small time offset between points on the tracker gauges due to misalignment or tilt of projectile impact on the HE; see for example [Menikoff, 2021b]. In addition, the thickness of the glue joints attaching the gauge package to the HE can affect the timing.

The 9012 experiments used a silicon glue, rather than the glue previously used for PBX 9501 and PBX 9502, due to an incompatibility. This resulted in much thicker glue joints. The effect of the thicker glue joints is discussed in [Menikoff, 2021a]. In comparison to previous PBX 9501 and PBX 9502 experiments, the 9012 tracker data displays a larger and variable time difference between corresponding points on different tracker gauges.

2 Tracker fits for shock trajectory of shot 1674

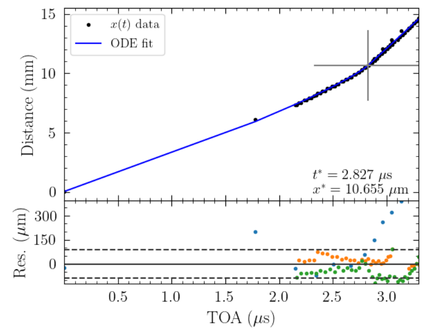
vel gauges (blue)
left tracker (orange)
right tracker (green)
center tracker (red)



$x_0 = 0.117\,\text{mm}$
$U_0 = 2.744\,\text{km/s}$
$U_{max} = 8.805\,\text{km/s}$
$a_{max} = 26.563\,\text{mm}/\mu\text{s}^2$
$D = 9.785\,\text{km/s}$

RMS residual $= 147\,\mu\text{m}$

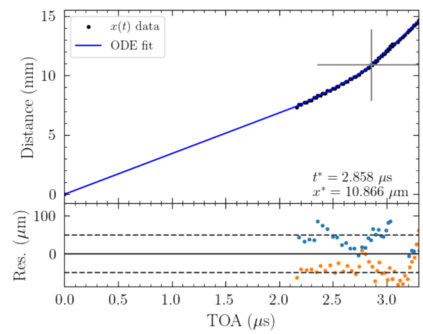
vel gauges (blue)
left tracker (orange)
right tracker (green)



$x_0 = 0.038\,\text{mm}$
$U_0 = 3.011\,\text{km/s}$
$U_{max} = 7.703\,\text{km/s}$
$a_{max} = 54.924\,\text{mm}/\mu\text{s}^2$
$D = 8.328\,\text{km/s}$

RMS residual $= 87\,\mu\text{m}$

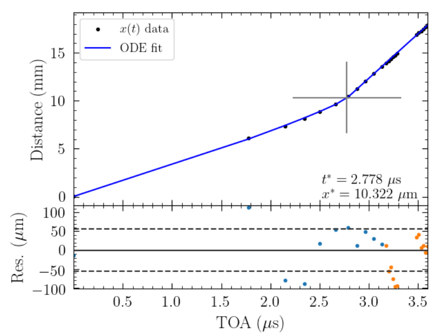
left tracker (blue)
right tracker (orange)



$x_0 = 0.000\,\text{mm}$
$U_0 = 2.984\,\text{km/s}$
$U_{max} = 7.730\,\text{km/s}$
$a_{max} = 38.453\,\text{mm}/\mu\text{s}^2$
$D = 8.407\,\text{km/s}$

RMS residual $= 50\,\mu\text{m}$

vel gauges (blue)
center tracker (orange)



$x_0 = 0.026\,\text{mm}$
$U_0 = 3.147\,\text{km/s}$
$U_{max} = 8.797\,\text{km/s}$
$a_{max} = 2071.6\,\text{mm}/\mu\text{s}^2$
$D = 9.273\,\text{km/s}$

RMS residual $= 56\,\mu\text{m}$

Figure 1: Fits to subsets of tracker data listed in left column. The residual, $x(t) - x_{fit}(t)$, is color coded by tracker gauge. Cross hairs correspond to transition point, which is listed at bottom-right of the trajectory plot. ODE parameters for each plot are listed to the right of each plot.

Observations on plots in fig. 1:

1. There are systematic differences between the residuals for the different tracker gauges. The differences are more than a constant offset or even a decreasing offset that is expected for tilt.

2. With all the tracker data (top plot), the transition point is over 1 mm (about 10 %) longer than shown in the other plots. It is also longer than a velocity gauge profile shows that the transition to detonation has occurred.

3. The late transition in the top plot is due to the center tracker data which is early by about the root mean square (RMS) of the residual. This affects the final detonation speed parameter D (roughly the slope of the $x(t)$ data after transition) which is over 12 percent larger than the CJ detonation speed of 1.860 km/s inferred from rate stick experiments.

4. All the center tracker data occurs after the transition, and hence should not affect the transition point. Leaving the center tracker data out of the fit (second plot) gives a transition consistent with the velocity gauge profiles. It also lowers the parameter D by 15 percent and reduces the RMS residual by 40 percent. More important, it increases the initial shock speed (parameter U_0) by about 10 percent and hence the shock pressure for the Pop plot data point is larger than inferred from the first fit.

5. The second residual plot shows that the last 4 gauge data points have a residual larger than the RMS residual. Leaving the gauge data points out of the fit (third plot) reduces the RMS residual by 42 percent with only small changes in the transition point, and parameters D and U_0.

6. The fourth plot uses only the velocity gauge data and the center tracker data. This is analogous to what Burns and Chiquete [2020] used for shot 1s1684 because the left and right trackers did not report (presumably due to a broken lead). Compared to the third plot, the parameters D and U_0 are high by 10 and 5 percent, respectively. In addition, the maximum acceleration parameter is almost an order of magnitude larger, which makes the transition very abrupt, see fig. 3. This is likely due to having few data points in the neighborhood of the transition.

7. Figure 2 compares the $x(t)$ trajectory for third and fourth fit. The trajectory is nearly the same before the transition but the slope is visibly different after the transition. It indicates that correlated changes in parameters can compensate for a change in the final slope when the transition is abrupt.

Since the transition to detonation is abrupt, the natural transition criterion is the point of maximum acceleration; *i.e.*, t such that $Us(t) = U_m$. The plots in fig. 1 use this criterion. Another frequently used criterion is $U_s(t) = 0.95\,D$. These two criterion on the shock speed time histories are shown in fig. 3. Since the slopes of $U_s(t)$ and $U_s(x)$ at the transition point are large, the two criterion give nearly the same run distance and time to detonation.

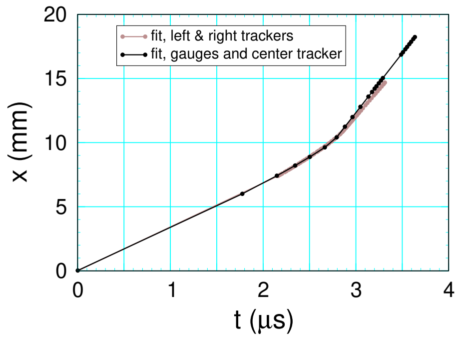


Figure 2: Comparison of fits for 2 subsets of tracker data.

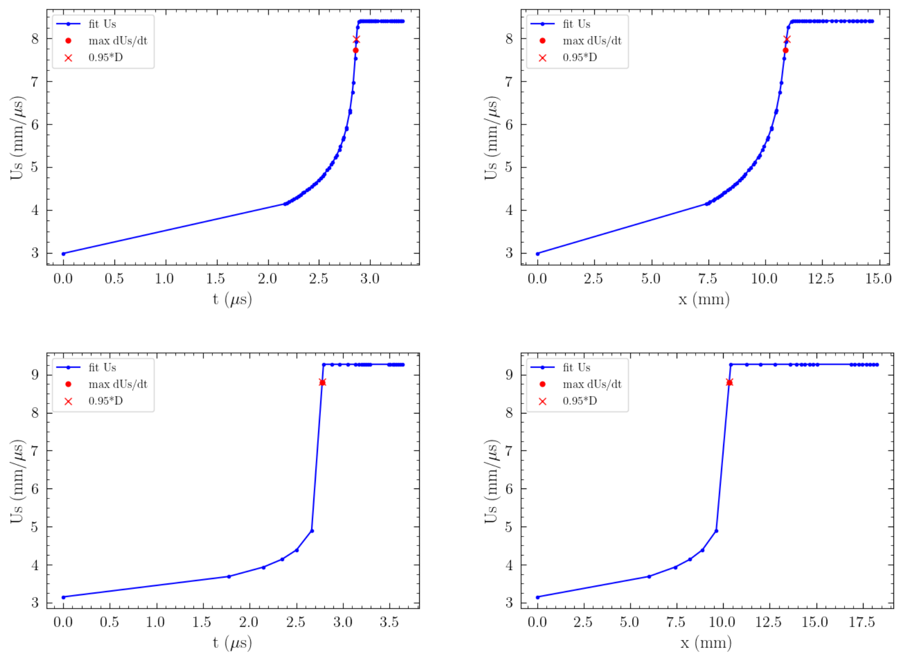


Figure 3: Transition at maximum acceleration and at shock velocity of $0.95\,D$. Top fit to left and right tracker data has moderate value of parameter $a_{max} = 38.5\,\mathrm{mm}/\mu\mathrm{s}^2$. Bottom fit to gauges and center tracker has large value of parameter $a_{max} = 2072\,\mathrm{mm}/\mu\mathrm{s}^2$.

3 Fit to simulated data

To distinguish the effects of uncertainties in the tracker data from uncertainties that arise from the fitting form, we have have performed the same fits as in the previous section with simulated data. The simulated data is from a numerical simulation of shot 1s1674 with a HE model. For the point of this exercise, it is not important whether the HE model is good or not. The simulated data shown in fig. 4 is physically plausible, highly resolved and with minimal random noise.

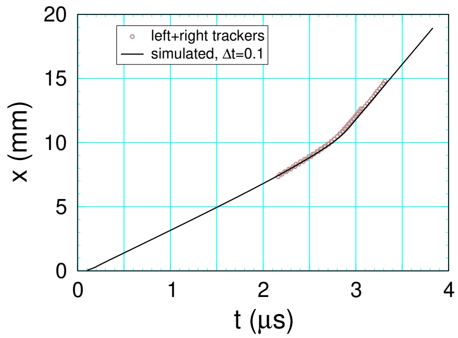
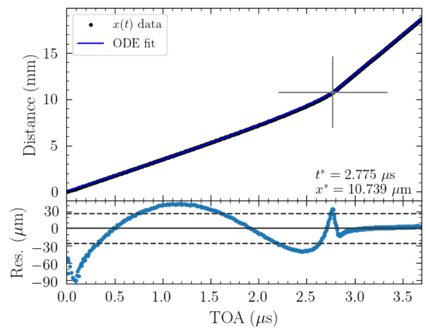


Figure 4: Simulated tracker data compared to experimental data from left and right trackers for shot 1s1674; third plot in fig. 1.

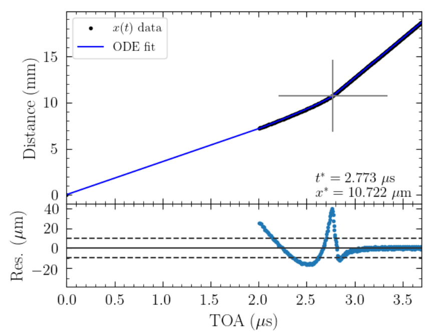
full domain



$x_0 = 0.078\,\text{mm}$
$U_0 = 3.280\,\text{km/s}$
$U_{max} = 8.095\,\text{km/s}$
$a_{max} = 324.4\,\text{mm}/\mu\text{s}^2$
$D = 8.588\,\text{km/s}$

RMS residual $= 26\,\mu\text{m}$

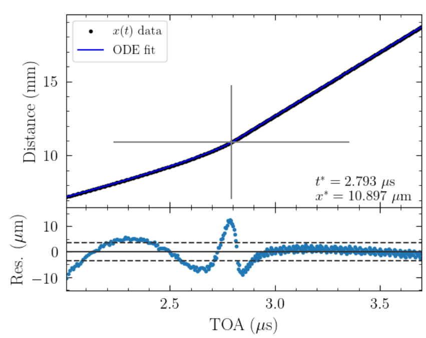
tracker gauge domain with point at origin



$x_0 = 0.034\,\text{mm}$
$U_0 = 3.278\,\text{km/s}$
$U_{max} = 8.089\,\text{km/s}$
$a_{max} = 274.7\,\text{mm}/\mu\text{s}^2$
$D = 8.592\,\text{km/s}$

RMS residual $= 9.7\,\mu\text{m}$

tracker gauge domain without point at origin



$x_0 = 7.229\,\text{mm}$ (at $t_0 = 2.007\,\mu\text{s}$)
$U_0 = 3.801\,\text{km/s}$
$U_{max} = 7.896\,\text{km/s}$
$a_{max} = 54.45\,\text{mm}/\mu\text{s}^2$
$D = 8.597\,\text{km/s}$

RMS residual $= 3.6\,\mu\text{m}$
integrate back to $t = 0$
$U_s = 2.742\,\text{km/s}$ & $x = 0.888\,\text{mm}$

Figure 5: Fits to simulated data.

Comments on fig. 5:

1. With all the simulated data (top plot) the RMS residual is small, $25\,\mu$m, which is about the spacing between the data points. The residual has a peak at the transition point. The odd behavior at the start of the trajectory is due to the start up error in the simulation; *i.e.*, when the numerical shock profile in the HE first forms.

2. The residual is due to the fitting form and not random errors in the data points. From the EOS used for the simulation to generate the data, the initial and final shock speeds are known. The fit parameter for the initial shock speed U_0 is 6 percent low, and the final shock speed D has a very small error, 0.03 percent low. The velocity error is due to the slope of the residual; $U_{s,\,fit}(t) = U_{s,\,data}(t) - (\mathsf{d}/\mathsf{d}t)$residual. We note the simulation shows that at the transition to detonation the lead shock pressure has a slight overshoot and then decays within 2 or 3 mm to nearly the steady state value. Consequently, the final shock speed of the simulated data is the CJ detonation speed.

3. The maximum acceleration is fairly large due to the high burn rate when the lead shock speed is in the detonation wave propagation regime. The parameter a_m is $324\,\mathrm{mm}/\mu\mathrm{s}^2$, but still may be limited by the resolutions of the trajectory data in the neighborhood of the transition; see fig. 6.

4. For the simulated data restricted to the domain of the tracker gauges with a point at the origin (second plot), the RMS residual is about half the spacing between data points and the peak at the transition point is a little more pronounced.

5. Without the point at origin or stirrup gauge data point (third plot), extrapolating (*i.e.*, integrating the ODEs back to $t = 0$) gives an initial shock speed $U_s(0)$ 16 percent lower than previous fits despite the very small RMS residual in the domain of the data. Hence, it is necessary to include the origin in order to get a good value for the initial shock speed.

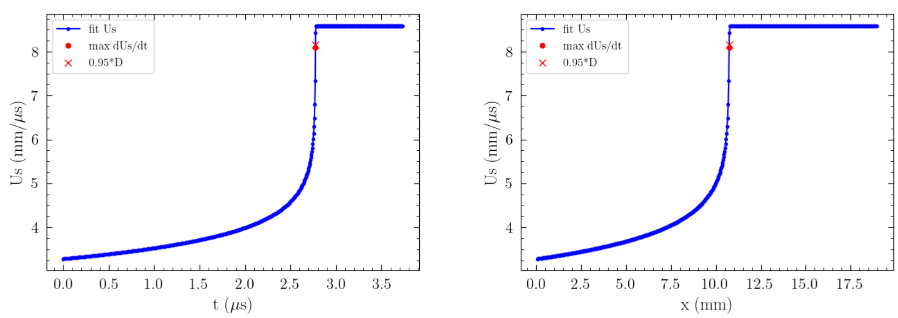


Figure 6: Shock velocity from ODE fit for simulated data vs t and vs x. Transition to detonation is indicated by red symbols.

Acknowledgement

Thanks to Matt Price for sharing python script that determines the ODE fit to trajectory data, and to Burns and Chiquete for placing their data in the smallscale database.

References

M. J. Burns and C. Chiquete. Shock initiation of the HMX-based explosive PBX 9012: Experiments, uncertainty analysis, and unreacted equation-of-state. *J. Appl. Phys.*, 127:215107, 2020. URL https://doi.org/10.1063/1.5144686.

L. G. Hill and R. L. Gustavsen. On the characterization and mechanisms of shock initiation in heterogeneous explosives. In *Proceeding of the Twelfth International Symposium on Detonation*, pages 975–987, 2002.

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